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# Interval Type-2 Fuzzy Logic System for Remote Vital Signs Monitoring and Shock Level Prediction

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## Abstract

Interval Type-2 Fuzzy Logic Systems (IT2 FLSs) have shown popularity, superiority, and more accuracy in performance in a number of applications in the last decade. This is due to its ability to cope with uncertainty and precisions adequately when compared with its type-1 counterpart. In this paper, an Interval Type-2 Fuzzy Logic System (IT2FLS) is employed for remote vital signs monitoring and predicting of shock level in cardiac patients. Also, the conventional, Type-1 Fuzzy Logic System (T1FLS) is applied to the prediction problems for comparison purpose. The cardiac patients' health datasets were used to perform empirical comparison on the developed system. The result of study indicated that IT2FLS could coped with more information and handled more uncertainties in health data than T1FLS. The statistical evaluation using performance metrices indicated a minimal error with IT2FLS compared to its counterpart, T1FLS. It was generally observed that the shock level prediction experiment for cardiac patients showed the superiority of IT2FLS paradigm over T1FLS.

**Keywords:** Uncertainty, Mamdani fuzzy inference, Cardiac patient, Health data, Deffuzification.

## 1 | Introduction



Non-linear problems, especially problems that are more relevant to everyday life activities cannot be solved with conventional models as they are not well suited. The increase in popularity of the fuzzy logic systems in problem solving can be attributed to its ability to incorporate human reasoning in its algorithm. The notion of Fuzzy Sets (FSs) was introduced in [1] as a method of representing uncertainty and vagueness in a way that elements are not limited to binary Membership Functions (MFs) of 0 or 1 but rather is a continuum in 0 and 1. A Type-1 Fuzzy System (T1FLS) is a rule based system which can be viewed as a process that maps crisp inputs to outputs by using the theory of fuzzy sets [2].

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T1FLSs have the ability to process information using linguistic variables and make decision with imprecise, vague, ambiguous and uncertain data. The beauty of T1FLSs is its' ability to represent nonlinear input/output relationships by using IF/THEN statements, called rules [3]. T1FLS consists of four components: fuzzifier, fuzzy rules, inference engine, and defuzzifier [4]. T1FLSs have achieved great success in handling many different real-world problems such as classification, regression, control, decision making, prediction, and so on [5-11]. However, due to the complexity and uncertainty in many real-world problems, T1FLs cannot adequately cope with or minimize the effects of the uncertainties posed by the complex nature of many real-world problems. These uncertainties can be as a result of uncertainty in inputs, uncertainty in outputs, uncertainty that is related to the linguistic differences, uncertainty caused by the change of conditions in the operation and uncertainty associated with the noisy data when training the fuzzy logic system [12].

In order to address this problem, [13] has recognized this potential limitation and introduced a higher type of fuzzy sets which is the concept of Type-2 Fuzzy Logic System (T2FLS) from Type-2 Fuzzy Set (T2FS). T2FLS is an extension of T1FLS with additional design degrees of freedom where the MFs are themselves fuzzy with the actual membership grade of an element assumed to lie within a closed interval of 0 and 1. However, T2FLS suffers computational complexity and to resolve this problem, Interval Type-2 Fuzzy Logic System (IT2FLS) is used which is a simplified version of T2FLS with reduced computational intensity making it quite practicable. Recently, T2FLSs and IT2FLSs have been successfully applied to handle a great deal of uncertainties in prediction problems and the results are very encouraging [14-15]. Consequently, IT2FLSs have dominated the research field and T2FLS are widely applied in various are due to their simpler structure and reduced computational cost [16]-[23].

In this study, remote vital signs monitoring and prediction of shock level in cardiac patients using an IT2FLS based on Mamdani fuzzy inference is presented. Our motivation is to apply IT2FS to reduce prediction error in the task of modeling uncertainties in health data. Mamdani Fuzzy Inference System (FIS) is employed as the background algorithm. Also, the study investigates the prediction of problems using conventional T1FLS for comparison purpose. The rest of the paper is structured as follows: Section 2 involves the preliminaries and reviews of the concepts on TIFS and IT2IFS. In Section 3, the design of IT2FLS for remote vital signs monitoring and prediction of shock level in cardiac patients is carried out. Our model results and discussion are presented in Section 4 and Section 5 involves conclusion of study.

## 2| An Overview of Type-1 and Interval Type-2 Fuzzy Sets

In this section, basic concepts of TIFS and IT2IFS are reviewed to deliver the fundamental knowledge required for comprehension of the work.

### 2.1| Type-1 Fuzzy Sets

According to [24], a classical fuzzy set otherwise called a T1FS, denoted by $A$, is characterized by a Type-1 Membership Function(T1MF), $\mu_A(x)$ where $x \in X$, and $X$ is the domain of definition of the variable as seen in *Eq. (1)*.

$$A = \{\{(x, \mu_A(x))\} | \forall x \in X\}. \tag{1}$$


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Where $\mu_A$ is called aType-1 membership function of T1FS, $A$ and maps each element of $A$ to a membership value called membership grade between 0 and 1. *Eqs. (2)* and *(3)* represent the T1FS, $A$ in its discrete and continuous forms respectively.

$$A = \mu_A(x_1)/x_1 + \mu_A(x_2)/x_2 + \cdots + \mu_A(x_n)/x_n, \quad (2)$$

$$A = \int_X \mu A(x)/x. \quad (3)$$

Where $x_1, x_2, x_n$ are members of fuzzy set $A$ and $\mu_A(x_1), \mu_A(x_2), \mu_A(x_n)$ are their respective membership grades.

## 2.2 | Type-1 Fuzzy Logic Systems (T1FLS)

The T1FLS also known as T1FIS is both, intuitive and numerical. The inference engine combines rules and gives a mapping from input type-1 fuzzy sets to output type-1 fuzzy sets. A fuzzy rule is a conditional statement in the form of IF-THEN where it contains two parts, the IF part called the antecedent part and the THEN part called the consequent part. Every T1FIS is associated with a set of rules obtained either from numerical data, or from problem domain experts with meaningful linguistic interpretations. In literature, we have two rules methods: Mamdani fuzzy rules [25] and [26] and Tagaki Sugeno Kang (TSK) [27] rules respectively. In Mamdani rule, the rule consequents are fuzzy sets while in TSK, the rule consequents are crisp functions of the inputs and can be illustrated in the form as follows:

$$\text{Mamdani: } R_k \text{IF } x_i \text{ is } A_i^k \text{and,., and } x_n \text{ is } A_n^k \text{ then } y_k \text{ is } B_i^k. \quad (4)$$

$$\text{TSK: } R_k \text{IF } x_i \text{ is } A_i^k \text{ and,., and } x_n \text{ is } A_n^k \text{ then } y_k = a * x_1 + b * x_2 + c. \quad (5)$$

Where, y is a T1FS, and a, b, c are crisp coefficients.

The membership grades in the fuzzy input sets are combined with those in the fuzzy output sets using the composition method and the outcome is combined with rules in an antecedent/consequent format, and then aggregated according to approximate reasoning theory. The structure of a T1FIS is shown in *Fig. 1* and consists of four basic components namely: the fuzzifier, the fuzzy rule-base, the inference engine, and the defuzzifier.

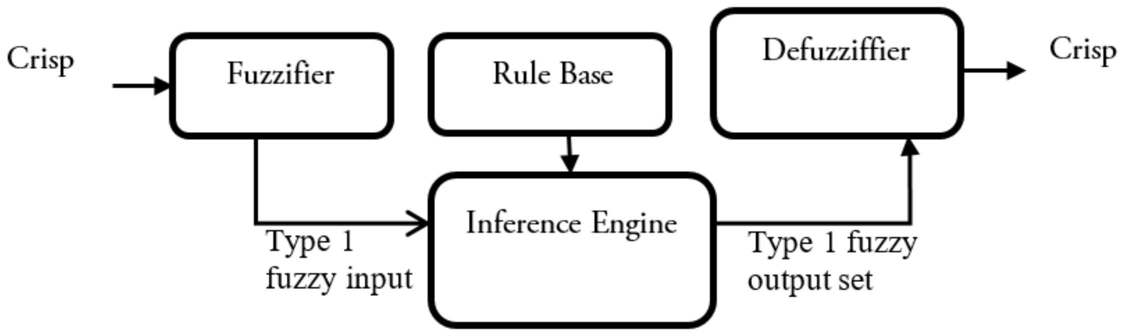


**Fig. 1. Structure of a type 1 fuzzy logic system [18].**

The fuzzifier maps the crisp input into a T1FS sets by evaluating the crisp inputs based on the antecedent part of the rules and assigns each crisp input a degree of membership in its input fuzzy set. The fuzzy rule-base is a collection of IF–THEN statements called rules in the form represented in *Eqs. (4)* and *(5)*. The inference engine combines the type-1 fuzzy input set and the rules to produce a type-1 fuzzy output and the defuzzifier maps the type-1 fuzzy output set, T1FSs that is produced by the inference engine into crisp values. The centroid of area defuzzification method based on [24] is applied to compute the crisp number as seen in *Eq. (6)*.

$$\text{Crisp Output, } Z = \sum_{i}^{n} \acute{Y}_k Z_k = \frac{\sum_{i=1}^{n} \acute{Y}_k Z_k}{\sum_{i=1}^{n} \acute{Y}_k} = \frac{\sum_{i=1}^{n} Z_k}{\sum_{i=1}^{n} Y_k}. \tag{6}$$

Where, $\sum_{i=1}^{n} \acute{Y}_k Z_k$ is the membership value in the membership function and $\acute{Y}_k$is the centre of membership function which is the running point in a discrete universe. The expression can be interpreted as the weighted average of the elements in the support set [28].

## 2.3 | Interval Type-2 Fuzzy Set (IT2FS)

An IT2FS is a simplified version of T2FS (1) introduced in [13] as an extension of T1FSand is characterized by a Type-2 Membership Function (T2MF), $\mu_{\tilde{A}}(x,u)$ and $0 \le \mu_{\tilde{A}}(x,u) \le 1$ as represented in *Eq. (7)* [12]. For an IT2FS, for which $X$ and $U$ are discrete, the domain of $\tilde{A}$ is equal to the union of all of its embedded T1 FSs as seen in *Eq. (8)*.

$$\tilde{A} = \left\{\left((x,u), \mu_{\tilde{A}}(x,u)\right) \middle| \forall\ x\ \in X, \forall\ u\ \in Jx \subseteq\ [0,1]\right., \tag{7}$$

$$\tilde{A} = \sum_{i=1}^{n}\left[\sum\nolimits_{u \in Jx}[1/u]\right]/x_i\ . \tag{8}$$

Where $x\ \in X$ and $u\ \in J \subseteq\ [0,1x]$; $x$ is the primary variable with a domain $X$ and $u \in U$ is the secondary variable with domain $J_x$ at each $x \in X$. $Jx$ is the primary membership of x and the secondary grades of all equal 1 [15, 18]. Hence, a type-2 membership grade can be any subset in [0, 1] [12]. Uncertainty about Ã is conveyed by the union of all the primary memberships, which is called the Footprint Of Uncertainty (FOU) of $A$ as shown in *Eq. (9)* and *Fig. 2,* respectively.

$$\mu_{\tilde{A}}(x,u) = 1, \text{FOU}\left(\tilde{A}\right) = \bigcup_{\forall x \in X} J_x = \{(x,u) : u\ \in Jx\ \subseteq\ [0,1]\}. \tag{9}$$

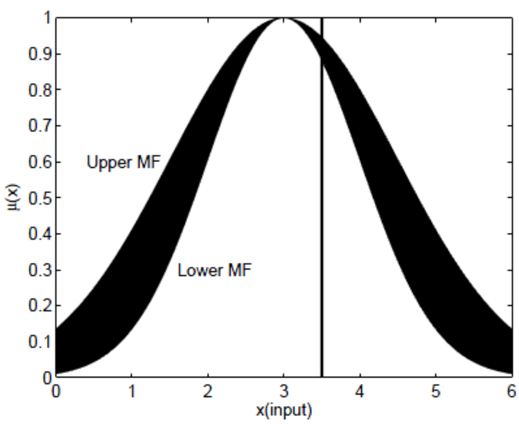


**Fig. 2. Interval type-2 fuzzy set [29].**

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The Upper Membership Function (UMF) and Lower Membership Function (LMF) of $\tilde{A}$comprises two type-1 MFs that bound the FOU. The UMF is associated with the upper bound of *FOU* ($\tilde{A}$) and is denoted by $\overline{\mu}_{\tilde{A}}(x)$, $\forall x\in X$, and the LMF is associated with the lower bound of *FOU* ($\tilde{A}$) and is denoted $\underline{\mu}_{\tilde{A}}(x)$, $\forall x\in X$, that is:

$$\overline{\mu}_{\tilde{A}}(x) \equiv \overline{\text{FOU}\left(\tilde{A}\right)} \quad \forall x \in X, \tag{10}$$

$$\underline{\mu}_{\tilde{A}}(x) \equiv \underline{\text{FOU}\left(\tilde{A}\right)} \quad \forall x \in X, \tag{11}$$

$$J_x = \{(x, u): u \in [\underline{\mu}_{\tilde{A}}(x), \overline{\mu}_{\tilde{A}}(x)]\}. \tag{12}$$

From *Eq. (3)*,

$$\tilde{A} = \text{FOU}\left(\tilde{A}\right) = \bigcup_{\forall x \in X} [\underline{\mu}_{\tilde{A}}(x), \overline{\mu}_{\tilde{A}}(x)]. \tag{13}$$

The LMF of $\tilde{A}$ are twice T1MFs bound the FOU in *Eqs.(9)* and *(10)* and $J_x$ is an interval set. The set theory operations of union, intersection and complement are applied to compute IT2FSs. For an IT2FS, for which $X$ and $U$ are discrete, the domain of $\tilde{A}$ is equal to the union of all of its embedded T1 FSs, so that $\tilde{A}$ can be expressed as;

$$\tilde{A} = 1/\text{FOU}\left(\tilde{A}\right) = 1/\bigcup_{x \in X}[\underline{\mu}_{\tilde{A}}(x), \overline{\mu}_{\tilde{A}}(x)]. \tag{14}$$

## 3 | Interval Type-2 Fuzzy Logic System (IT2FLS)

*Fig. 3* shows a structure of an IT2FLS which is a version of T2FL. IT2FLS is a FLS that uses at least one IT2FS in mapping from crisp inputs to crisp outputs. IT2FLS is employed to reduce the computational burden of T2FLS while preserving the advantages of T2FLS. T1FLS cannot adequately handle the effect of uncertainties posed by the complex nature of real-world data because it uses T1FS which is characterized by membership functions that are certain. To address this problem, IT2FL is introduced as an extension of T1FL to provide additional design degrees of freedom with membership functions that are themselves fuzzy. IT2FL can be very useful when used in situations where lots of uncertainties are presented and have the potential to provide better performance than T1FLS. An IT2FIS is characterized by five components: a fuzzifier, a rule-base, an inference-engine, type-reducer and defuzzifier - that are inter-connected. Also, an IT2FIS is characterized by IF–THEN rules, in this case, the antecedent and consequents parts are Type-2 fuzzy sets [12].

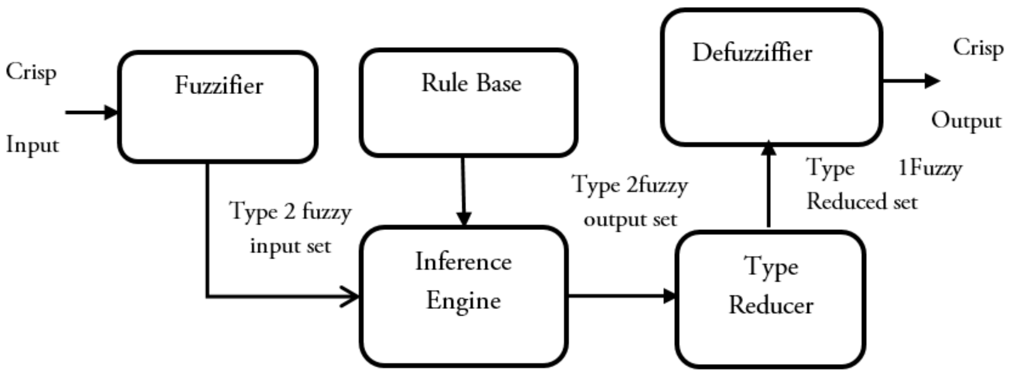


**Fig. 3. The structure of a type -2 fuzzy logic system [30].**

$$\text{Mamdani: } R_k \text{IF } x_i \text{ is } \widetilde{A}_i^k \text{ and, ... , and } x_n \text{ is } \widetilde{A}_n^k \text{ then } y_k \text{ is } \tilde{B}_i^k. \tag{15}$$

Where $x_i$, $i = 1, 2\ldots, n$ are the antecedents, $y$ is the consequent of the k*th* rule of IT2FLS. The $\tilde{A}^i$'s are the MFs $\mu_{\tilde{A}_i^k}(x_i)$ of antecedent part of the *i*th input $x_i$, The $B^i$ is the MFs $\mu_{\tilde{B}_i^k}(y)$ of the consequent part of the output $y_j$. The firing strength is evaluated from the input and antecedent operations to produce an IT1 set [31].

$$F^i(x') = [\underline{f}'(x'), \overline{f}'(x')] \equiv [\underline{f}', \overline{f}'] \tag{16}$$

Where $F^i(x')$ is the antecedent of rule $i$ and $\mu_{F'^i}(x')$ is the degree of membership of $x$ in $F.\overline{\mu}_{\tilde{f}^i}(x)$ and $\underline{\mu}_{\tilde{f}^i}(x)$ are upper and lower MFs of $\mu_{\tilde{f}^i}$, $i = 1$ to $m$ respectively. The inference engine combines the fired rules to produce a mapping from input to output in IT2FSs. The output fuzzy set, $\mu_{\tilde{E}_j^l}(y_j)$, is evaluated by combining the fired output consequent sets through the union of the kth rule fired output consequent sets. An exact iterative method of type-reduction is performed to compute the centroid of an *IT2FS* which is a T1FS. The type-reduced set gives an interval of uncertainty for the output of an IT2FLS: the more uncertainties in IT2FLS, the more uncertainties about its MFs and the larger the type-reduced set, and vice-versa. IT2FS are characterized by their left- and right-end points required to compute the centroid of an IT2FS [12], [32] and a detailed definition oftype-reduction *Eq. (17)* can be found in [15] and [30], [31] respectively. In this paper, we adopt Karnik and Mendel (KM), Algorithms [32] to calculate the exact end-points in *Eqs.(18)* and *(19)*, respectively we obtain the defuzzified crisp output for each output *k* using *Eq. (20)*.

$$\begin{aligned} Y_{TR}(x') &= [y_l(x'), y_r(x')] \equiv [y_l, y_r] \\ &= \int_{y^1 \in [y_l^1, y_r^1]} \cdots \int_{y^1 \in [y_l^N, y_r^N]} \int_{f^1 \in [\underline{f}^1, \overline{f}^1]} \cdots \int_{f^N \in [\underline{f}^N, \overline{f}^N]} 1 \Big/ \frac{\sum_{i=1}^N f^i y^i}{\sum_{i=1}^N f^i}. \end{aligned} \tag{17}$$

$$y_r = \frac{\sum_{i=1}^N f_r^i y_r^i}{\sum_{i=1}^N f_r^i}. \tag{18}$$

$$y_l = \frac{\sum_{i=1}^N f_l^i y_l^i}{\sum_{i=1}^N f_l^i}. \tag{19}$$

$$Y_k(X) = \frac{y_{lk} + y_{rk}}{2}. \tag{20}$$

The performance criteria in *Eqs. (21)* and *(22)* are defined and applied to measure our experimental results: Mean Squared Error (MSE) and Root Mean Squared Error (RMSE).

$$\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} (y^x - y)^2, \tag{21}$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y^x - y)^2}. \tag{22}$$

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Where $y^x$ is desired output, y is the computed output and N is the number of data items, respectively.

# 4 | Model Experiment

The model experiment was carried out in two (2) major stages namely: clinical data collection and design of interval type-2 fuzzy logic model for prediction problems in patients. Data of cardiovascular patients were collected. The data were pre-processed and stored in a database. The interval type-2 fuzzy logic model was designed. Inputs to the model were systolic blood pressure, diastolic blood pressure, temperature, heart rate and respiratory rate while cardiac shock level served as the desired output. The model employed, triangular membership function, Mamdani inference strategy, Karnik-Mendel reduction method and centroid deffuzification process for cardiac shock prediction in patients.

## 4.1 | Clinical Data Collection

Clinical data were collected for cardiovascular patients at the Federal Medical Centre Yenagoa, Bayelsa, Nigeria and University of Uyo Teaching Hospital, Akwa Ibom State, Nigeria, respectively for the period of 2016-2018. To represent ethical concerns, a written permission was processed and duly approved before data collection commenced. Expert knowledge on cardiovascular disease and disease diagnosis was captured with 50 questionnaire and interview from the head of cardiology unit in the department of medicine in both Federal Medical Centre, Yenagoa, Bayelsa State, Nigeria and University of Uyo Teaching Hospital, Akwa Ibom State, Nigeria, respectively. A total of 1000 patients sample data were obtained from the University of Uyo Teaching Hospital, and in the Federal Medical Centre Yenagoa, Bayelsa, Nigeria. The sample dataset for the first 35 patients extracted from Federal Medical Centre Yenagoa are presented in the *Table 1*.

## 4.2 | Interval Type-2 Fuzzy Logic Model for Prediction Problems in Patients

The data collected in Section 4.1 were stored in a database and served as input to the interval type-2 fuzzy logic controller. In the fuzzy controller system, the data were fuzzified using fuzzy linguistic variable and membership triangular membership function. Inference was made based on fuzzy rules which produced interval type 2 fuzzy set. Karnik-Mendel method was employed to reduce the type 2 fuzzy set to type 1 fuzzy set. The fuzzy output was obtained through centroid defuzziffication process. Notification message module was incorporated in the system. This would enable alerts and vital information to be sent to doctors-on-call, caregivers, ambulance agency and designated family members for necessary action based on detection threshold from the cardiac shock prediction results. Interval Type-2 Fuzzy logic frameworks for prediction problems in cardiac patient is presented in *Fig. 4*.

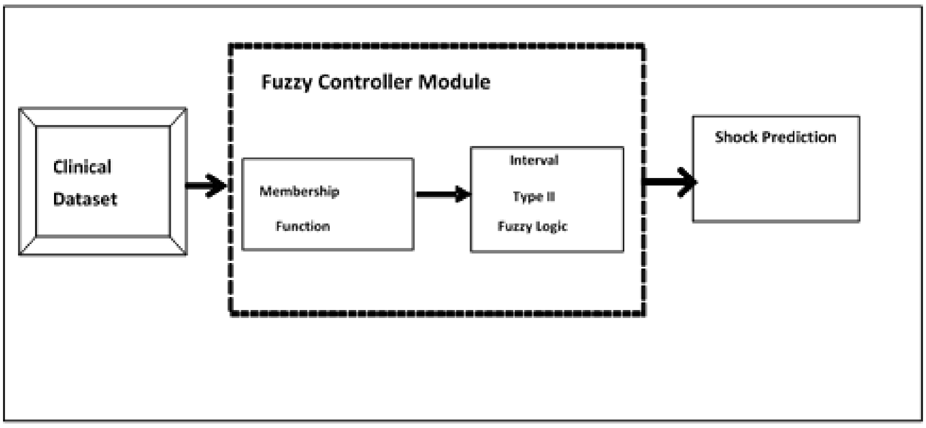


Fig. 4. Interval type-2 fuzzy logic framework for prediction problems in cardiac patient.

Table 1. Sample data extraction from Federal Medical Centre Yenagoa, Bayelsa.

| Age | Sex | BPDiastolic | BPSystolic | Temp oC | Weight (kg) | Respiratory Rate(cm) | Pulse Rate(b/m) |
|---|---|---|---|---|---|---|---|
| 70 | F | 120 | 90 | 36.9 | 82 | 20 | 80 |
| 53 | F | 140 | 100 | 36.7 | 90 | 22 | 68 |
| 60 | M | 170 | 100 | 36.1 | 77.4 | 24 | 120 |
| 45 | M | 100 | 70 | 35.2 | 80 | 22 | 70 |
| 57 | M | 105 | 70 | 36.9 | 79 | 18 | 122 |
| 63 | F | 170 | 90 | 36.2 | 77.4 | 20 | 80 |
| 37 | M | 125 | 80 | 36.4 | 62.5 | 20 | 80 |
| 41 | F | 120 | 70 | 35.2 | 55 | 20 | 86 |
| 56 | M | 130 | 90 | 36.8 | 92 | 20 | 80 |
| 60 | F | 150 | 110 | 36.9 | 77.4 | 20 | 86 |
| 57 | M | 98 | 60 | 36.6 | 91 | 20 | 76 |
| 56 | M | 120 | 80 | 36.2 | 79 | 22 | 73 |
| 44 | M | 140 | 90 | 36.9 | 55 | 20 | 80 |
| 52 | M | 120 | 90 | 36.7 | 48 | 20 | 90 |
| 57 | F | 150 | 120 | 39 | 50 | 22 | 80 |
| 54 | M | 120 | 80 | 36.8 | 80 | 24 | 78 |
| 48 | M | 112 | 60 | 36.7 | 50 | 24 | 62 |
| 49 | F | 110 | 80 | 36.3 | 41.4 | 20 | 60 |
| 64 | F | 140 | 80 | 36.7 | 94.1 | 16 | 78 |
| 58 | F | 120 | 70 | 36.7 | 80 | 20 | 82 |
| 50 | F | 130 | 80 | 36.4 | 49.8 | 20 | 68 |
| 59 | M | 130 | 100 | 36.1 | 53 | 22 | 90 |
| 66 | F | 150 | 90 | 36.4 | 93 | 21 | 78 |
| 43 | M | 130 | 80 | 36.5 | 50.6 | 23 | 64 |
| 69 | M | 160 | 90 | 36.7 | 96.5 | 20 | 80 |
| 59 | M | 130 | 90 | 36.4 | 51.2 | 19 | 68 |
| 44 | M | 120 | 80 | 36.7 | 68 | 17 | 59 |
| 42 | M | 140 | 80 | 36.7 | 71 | 20 | 72 |
| 61 | F | 145 | 100 | 36.8 | 58 | 22 | 85 |
| 40 | M | 90 | 70 | 35.1 | 62 | 24 | 69 |
| 71 | M | 120 | 70 | 36.3 | 50 | 20 | 70 |
| 59 | F | 120 | 80 | 36.4 | 70 | 22 | 90 |
| 51 | M | 120 | 80 | 37.4 | 60 | 21 | 80 |
| 65 | F | 130 | 80 | 36.3 | 68.8 | 20 | 68 |
| 53 | M | 190 | 110 | 36.1 | 59.5 | 24 | 78 |

In this paper, derived input parameters are defined as temperature, heart rate, blood pressure and respiratory rate, the membership functions and the associated linguistic variables, the universe of discourse and fuzzy linguistic variable are well defined. *Table 2* presents the input variables and the universe of discourse.

**Table 2. The input variables and the universe of discourse.**

| Input Variables and their Universe of Discourse | | | | | |
|---|---|---|---|---|---|
| **Heart Rate** | **Respiratory Rate** | **Body Temperature** | **Blood Pressure** | | **Prediction** |
| | | | **Systolic** | **Diastolic** | |
| [0, 200] | [0, 60] | [0 ,41.5] | [0, 200] | [0, 150] | [0 , 1] |

Triangular Membership Function (TMF) method in *Eq. (23)* was used to evaluate each input and output Membership Functions (MFs) as follows:

$$\mu_A(x) = \begin{cases} 0 & \text{if } x \leq a \\ \frac{x-a}{b-a} & \text{if } a \leq x \leq b \\ \frac{c-x}{c-b} & \text{if } b \leq x \leq c \\ 0 & \text{if } x \geq a \end{cases}. \tag{23}$$

Where, a, b, c represent the x coordinates of the three vertices of $\mu_A(x)$in a fuzzy set A. a , c is the lower boundary and Upper boundary where membership degree is zero respectively, b is the centre where membership degree is 1 . x is the coordinate of three vertices (taking by assumption). The IT2FL UMF and LMF are derived from general model in *Eqs.(24)* and *(25)* and evaluated for all the input variables respectively. The Membership function values for shock prediction are shown in *Table 3*.

$$\begin{pmatrix} \bar{\mu}(x) \\ \text{IT2FL UMF} \end{pmatrix} = \begin{cases} 0, & x \leq y_1 \\ \frac{x-y_1}{q_1-y_1}, & \text{if } y_1 \leq x \leq q_1 \\ 1, & \text{if } q_1 \leq x \leq r_2 \\ \frac{r_2-x}{r_2-q_2}, & \text{if } q_2 \leq x \leq r_2 \end{cases}. \tag{24}$$

$$\begin{pmatrix} \underline{\mu}(x) \\ \text{IT2FL LMF} \end{pmatrix} = \begin{cases} 0, & x \leq y_2 \\ \frac{x-y_2}{q_2-y_2}, & \text{if } y_2 \leq x \leq \frac{r_1(q_2-y_2)+y_2(r_1-q_1)}{(q_2-y_2)+(r_1-q_1)} \\ \frac{r_2-x}{r_2-q_2}, & \text{if } x > \frac{r_1(q_2-y_2)+y_2(r_1-q_1)}{(q_2-y_2)+(r_1-q_1)} < x < r_1 \\ 0, & \text{if } x \geq r_2 \end{cases}. \tag{25}$$

Where *y* is left end point of both UMF and LMF and *r* is right end point of both UMF and LMF and *q* is the peak point.

Respiratory rate UMF and LMF (low)

$$\overline{\mu}_{RR}(low)(x) = \begin{cases} 0, & x \le 0.0863 \\ \frac{x-0.0863}{q_1 - 0.0863}, & if\ 0.0863 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \frac{13.4-x}{13.4-q_2}, & if\ q_2 \le x \le 13.4 \\ 0, & if\ x > 13.4 \end{cases}$$

$$\underline{\mu}_{RR}(low)(x) = \begin{cases} 0, & x \le 1.69 \\ \frac{x-y_2}{q_2 - y_2}, & if\ 1.69 \le x \le \frac{12.01(q_2-1.69)+1.69(12.01-q_1)}{(q_2-1.69)+(12.01-q_1)} \\ \frac{13.4-x}{13.4-q_2}, & if\ x > \frac{12.01(q_2-1.69)+1.69(12.01-q_1)<x<12.01}{(q_2-1.69)+(12.01-q_1)} \\ 0, & if\ x \ge 13.4 \end{cases}$$

Respiratory Rate UMF and LMF Normal (NM)

$$\overline{\mu}_{RR}(N)(x) = \begin{cases} 0, & \le 7.61 \\ \frac{x-7.61}{q_1 - 7.61}, & if\ 7.61 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \frac{29.6-x}{29.6-q_2}, & if\ q_2 \le x \le 29.6 \\ 0, if\ x > 29.6 \end{cases}$$

$$\underline{\mu}_{RR}(N)(x) = \begin{cases} 0, & x \le 10.13 \\ \frac{x-10.13}{q_2 - 10.13}, & if\ 10.13 \le x \le \frac{26.8(q_2-10.13)+10.13(26.8-q_1)}{(q_2-10.13)+(26.8-q_1)} \\ \frac{29.6-x}{29.6-q_2}, & if\ x > \frac{26.8(q_2-10.13)+10.13(26.8-q_1)<x<26.8}{(q_2-10.13)+(26.8-q_1)} \\ 0, & if\ x \ge 29.6 \end{cases}$$

For Respiratory Rate UMF and LMF High (H)

$$\overline{\mu}_{RR}(H)(x) = \begin{cases} 0, & x \le 22.8 \\ \frac{x-22.8}{q_1 - 22.8}, & if\ 22.8 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \frac{59.8-x}{59.8-q_2}, & if\ q_2 \le x \le 59.8 \\ 0, if\ x > 59.8 \end{cases}$$

$$\underline{\mu}_{RR}(H)(x) = \begin{cases} 0, & x \le 26.1 \\ \frac{x-26.1}{q_2 - 26.1}, & \text{if } 26.1 \le x \le \frac{54.8(q_2-26.1)+26.1(54.8-q_1)}{(q_2-26.1)+(26.8-q_1)} \\ \frac{59.8-x}{59.8-q_2}, & \text{if } x > \frac{54.8(q_2-26.1)+26.1(54.8-q_1)<x<54.8}{(q_2-26.1)+(54.8-q_1)} \\ 0, & \text{if } x \ge 59.8 \end{cases}$$

For Heart Rate UMF and LMF low (L)

$$\overline{\mu}_{HR}(L)(x) = \begin{cases} 0, & x \le -0.208 \\ \frac{x-(-0.208)}{q_1 - (-0.208)}, & if\ -0.208 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \frac{60-x}{60-q_2}, & if\ q_2 \le x \le 60 \\ 0, if\ x > 60 \end{cases}$$

$$\underline{\mu}_{HR}(L)(x) = \begin{cases} 0, & x \le 4.48 \\ \frac{x-4.48}{q_2 - 4.48}, & if\ 4.48 \le x \le \frac{56.2(q_2-4.48)+4.48(56.2-q_1)}{(q_2-4.48)+(56.2-q_1)} \\ \frac{60-x}{60-q_2}, & if\ x > \frac{56.2(q_2-4.48)+4.48(56.2-q_1)<x56.2}{(q_2-4.48)+(56.2-q_1)} \\ 0, & if\ x \ge 60 \end{cases}$$

For Heart Rate UMF and LMF Normal (N)

$$\overline{\mu}_{HR}(N)(x) = \begin{cases} 0, & x \le 49.5 \\ \dfrac{x-49.5}{q_1-49.5}, & if\ 49.5 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{123-x}{123-q_2}, & if\ q_2 \le x \le 123 \\ 0, & if\ x > 123 \end{cases}$$

$$\underline{\mu}_{HR}(N)(x) = \begin{cases} 0, & x \le 53.03 \\ \dfrac{x-53.03}{q_2-53.03}, & if\ 4.48 \le x \le \dfrac{56.2(q_2-53.03)+53.03(56.2-q_1)}{(q_2-53.03)+(56.2-q_1)} \\ \dfrac{123-x}{123-q_2}, & if\ x > \dfrac{119(q_2-53.03)+53.03(119-q_1)<x119}{(q_2-53.03)+(119-q_1)} \\ 0, & if\ x \ge 123 \end{cases}$$

For Heart Rate UMF and LMF High (H)

$$\overline{\mu}_{HR}(H)(x) = \begin{cases} 0, & x \le 107 \\ \dfrac{x-107}{q_1-107}, & if\ 107 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{198-x}{198-q_2}, & if\ q_2 \le x \le 198 \\ 0, & if\ x > 198 \end{cases}$$

$$\underline{\mu}_{HR}(H)(x) = \begin{cases} 0, & x \le 111 \\ \dfrac{x-111}{q_2-111}, & if\ 111 \le x \le \dfrac{191(q_2-111)+111(191-q_1)}{(q_2-111)+(191-q_1)} \\ \dfrac{198-x}{198-q_2}, & if\ x > \dfrac{191(q_2-111)+111(191-q_1)<x191}{(q_2-111)+(191-q_1)} \\ 0, & if\ x \ge 198 \end{cases}$$

For Body Temperature UMF and LMF (low)

$$\overline{\mu}_{Temp}(low)(x) = \begin{cases} 0, & x \le 0.145 \\ \dfrac{x-0.145}{q_1-0.145}, & if\ 0.145 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{22.5-x}{22.5-q_2}, & if\ q_2 \le x \le 22.5 \\ 0, & if\ x > 22.5 \end{cases}$$

$$\underline{\mu}_{Temp}(low)(x) = \begin{cases} 0, & x \le 1.85 \\ \dfrac{x-1.85}{q_2-1.85}, & if\ 1.85 \le x \le \dfrac{20.3(q_2-1.85)+1.85(20.3-q_1)}{(q_2-1.85)+(20.3-q_1)} \\ \dfrac{22.5-x}{22.5-q_2}, & if\ x > \dfrac{20.3(q_2-1.85)+1.85(20.3-q_1)<x20.3}{(q_2-1.85)+(20.3-q_1)} \\ 0, & if\ x \ge 22.5 \end{cases}$$

For Body Temperature UMF and LMF (No

$$\overline{\mu}_{Temp}(normal)(x) = \begin{cases} 0, & x \le 9.59 \\ \dfrac{x-9.59}{q_1-9.59}, & if\ 9.59 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{30.02-x}{30.02-q_2}, & if\ q_2 \le x \le 30.02 \\ 0, & if\ x > 30.02 \end{cases}$$

$$\underline{\mu}_{Temp}(normal)(x) = \begin{cases} 0, & x \le 11.48 \\ \dfrac{x-11.48}{q_2-11.48}, & if\ 11.48 \le x \le \dfrac{28.3(q_2-11.48)+11.48(28.3-q_1)}{(q_2-11.48)+(28.3-q_1)} \\ \dfrac{30.02-x}{30.02-q_2}, & if\ x > \dfrac{28.3(q_2-11.48)+11.48(28.3-q_1)<x28.3}{(q_2-11.48)+(28.3-q_1)} \\ 0, & if\ x \ge 30.02 \end{cases}$$

For Body Temperature UMF and LMF (High)

$$\overline{\mu}_{Temp}(high)(x) = \begin{cases} 0, & x \le 25.1 \\ \dfrac{x-25.1}{q_1-25.1}, & if\ 25.1 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{37.7-x}{37.7-q_2}, & if\ q_2 \le x \le 37.7 \\ 0, & if\ x > 37.7 \end{cases}$$

$$\underline{\mu}_{Temp}(high)(x) = \begin{cases} 0, & x \le 26.0 \\ \dfrac{x-26.0}{q_2-26.0}, & if\ 26.0 \le x \le \dfrac{36.3(q_2-26.0)+26.0(36.3-q_1)}{(q_2-26.0)+(36.3-q_1)} \\ \dfrac{37.7-x}{37.7-q_2}, & if\ x > \dfrac{36.3(q_2-26.0)+26.0(36.3-q_1)<x36.3}{(q_2-26.0)+(36.3-q_1)} \\ 0, & if\ x \ge 37.7 \end{cases}$$

For Body Temperature UMF and LMF very high

$$\overline{\mu}_{Temp}(veryhigh)(x) = \begin{cases} 0, & x \le 30.5 \\ \dfrac{x-30.5}{q_1-30.5}, & if\ 30.5 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{41.4-x}{41.4-q_2}, & if\ q_2 \le x \le 41.4 \\ 0, & if\ x > 41.4 \end{cases}$$

$$\underline{\mu}_{Temp}(veryhigh)(x) = \begin{cases} 0, & x \le 31.9 \\ \dfrac{x-31.9}{q_2-31.9}, & if\ 31.9 \le x \le \dfrac{40(q_2-31.9)+31.9(40-q_1)}{(q_2-31.9)+(40-q_1)} \\ \dfrac{41.4-x}{41.4-q_2}, & if\ x > \dfrac{40(q_2-31.9)+31.9(40-q_1)<x<40}{(q_2-31.9)+(40-q_1)} \\ 0, & if\ x \ge 41.4 \end{cases}$$

For Systolic Blood Pressure UMF and LMF for Low

$$\overline{\mu}_{systolicBP}(low)(x) = \begin{cases} 0, & x \le 2.34 \\ \dfrac{x-2.34}{q_1-2.34}, & if\ 2.34 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{90.03-x}{90.03-q_2}, & if\ q_2 \le x \le 90.03 \\ 0, & if\ x > 90.03 \end{cases}$$

$$\underline{\mu}_{systolicBP}(low)(x) = \begin{cases} 0, & x \le 11.2 \\ \dfrac{x-11.2}{q_2-11.2}, & if\ 11.2 \le x \le \dfrac{84(q_2-11.2)+11.2(84-q_1)}{(q_2-11.2)+(84-q_1)} \\ \dfrac{90.03-x}{90.03-q_2}, & if\ x > \dfrac{84(q_2-11.2)+11.2(84-q_1)<x<84}{(q_2-11.2)+(84-q_1)} \\ 0, & if\ x \ge 90.03 \end{cases}$$

For Systolic Blood Pressure UMF and LMF (Normal)

$$\overline{\mu}_{systolicBP}(normal)(x) = \begin{cases} 0, & x \le 74.42 \\ \dfrac{x-74.42}{q_1-74.42}, & if\ 74.42 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{139-x}{139-q_2}, & if\ q_2 \le x \le 139 \\ 0, & if\ x > 139 \end{cases}$$

$$\underline{\mu}_{systolicBP}(normal)(x) = \begin{cases} 0, & x \le 78.76 \\ \dfrac{x-78.76}{q_2-78.76}, & if\ 78.76 \le x \le \dfrac{135(q_2-78.76)+78.76(135-q_1)}{(q_2-78.76)+(135-q_1)} \\ \dfrac{139-x}{139-q_2}, & if\ x > \dfrac{135(q_2-78.76)+78.76(135-q_1)<x<135}{(q_2-78.76)+(135-q_1)} \\ 0, & if\ x \ge 139 \end{cases}$$

For Systolic Blood Pressure UMF and LMF (High)

$$\overline{\mu}_{systolicBP}(high)(x) = \begin{cases} 0, & x \leq 151 \\ \frac{x-151}{q_1-151}, & if 151 \leq x \leq q_1 \\ 1, & if\ q_1 \leq x \leq q_2 \\ \frac{159.7-x}{159.7-q_2}, & if\ q_2 \leq x \leq 159.7 \\ 0, & if\ x > 159.7 \end{cases}$$

$$\underline{\mu}_{systolicBP}(high)(x) = \begin{cases} 0, & x \leq 128 \\ \frac{x-128}{q_2-128}, & if\ 128 \leq x \leq \frac{154(q_2-128)+128(154-q_1)}{(q_2-128)+(154-q_1)} \\ \frac{159.7-x}{159.7-q_2}, & if\ x > \frac{154(q_2-128)+128(154-q_1)<x<154}{(q_2-128)+(154-q_1)} \\ 0, & if\ x \geq 159.7 \end{cases}$$

For Systolic Blood Pressure UMF and LMF Very High

$$\overline{\mu}_{systolicBP}(veryhigh)(x) = \begin{cases} 0, & x \leq 151 \\ \frac{x-151}{q_1-151}, & if\ 151 \leq x \leq q_1 \\ 1, & if\ q_1 \leq x \leq q_2 \\ \frac{179.9-x}{179.9-q_2}, & if\ q_2 \leq x \leq 179.9 \\ 0, & if\ x > 179.9 \end{cases}$$

$$\underline{\mu}_{systolicBP}(veryhigh)(x) = \begin{cases} 0, & x \leq 155 \\ \frac{x-155}{q_2-155}, & if\ 155 \leq x \leq \frac{177(q_2-155)+155(177-q_1)}{(q_2-155)+(177-q_1)} \\ \frac{179.9-x}{179.9-q_2}, & if\ x > \frac{177(q_2-155)+155(177-q_1)<x<177}{(q_2-155)+(177-q_1)} \\ 0, & if\ x \geq 179.9 \end{cases}$$

For Systolic Blood Pressure UMF and LMF Severe

$$\overline{\mu}_{systolicBP}(severe)(x) = \begin{cases} 0, & x \leq 171 \\ \frac{x-171}{q_1-171}, & if\ 171 \leq x \leq q_1 \\ 1, & if\ q_1 \leq x \leq q_2 \\ \frac{198-x}{198-q_2}, & if\ q_2 \leq x \leq 198 \\ 0, & if\ x > 198 \end{cases}$$

$$\underline{\mu}_{systolicBP}(veryhigh)(x) = \begin{cases} 0, & x \leq 174 \\ \frac{x-174}{q_2-174}, & if 174 \leq x \leq \frac{194(q_2-174)+174(194-q_1)}{(q_2-174)+(194-q_1)} \\ \frac{198-x}{198-q_2}, & if\ x > \frac{194(q_2-174)+174(194-q_1)<x<194}{(q_2-174)+(194-q_1)} \\ 0, & if\ x \geq 198 \end{cases}$$

For Diastolic Blood Pressure UMF and LMF Low

$$\overline{\mu}_{DiastolicBP}(low)(x) = \begin{cases} 0, & x \leq 1.778 \\ \frac{x-1.778}{q_1-1.778}, & if\ 1.778 \leq x \leq q_1 \\ 1, & if\ q_1 \leq x \leq q_2 \\ \frac{67.53-x}{67.53-q_2}, & if\ q_2 \leq x \leq 67.53 \\ 0, & if\ x > 67.53 \end{cases}$$

$$\underline{\mu}_{DiastolicBP}(low)(x) = \begin{cases} 0, & x \leq 6.45 \\ \frac{x-6.45}{q_2-6.45}, & if 6.45 \leq x \leq \frac{63.84(q_2-6.45)+6.45(63.84-q_1)}{(q_2-6.45)+(63.84-q_1)} \\ \frac{67.53-x}{67.53-q_2}, & if\ x > \frac{63.84(q_2-6.45)+6.45(63.84-q_1)<x<63.84}{(q_2-6.45)+(63.84-q_1)} \\ 0, & if\ x \geq 67,53 \end{cases}$$

For Diastolic Blood Pressure UMF and LMF Normal

$$\overline{\mu}_{DiastolicBP}(Normal)(x) = \begin{cases} 0, & x \le 54.29 \\ \dfrac{x-54.29}{q_1 - 54.29}, & if\ 54.29 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{102.8-x}{102.8-q_2}, & if\ q_2 \le x \le 102.8 \\ 0, & if\ x > 102.8 \end{cases}$$

$$\underline{\mu}_{DiastolicBP}(Normal)(x) = \begin{cases} 0, & x \le 57.3 \\ \dfrac{x-57.3}{q_2 - 57.3}, & if 57.3 \le x \le \dfrac{98.5(q_2 - 57.3)+57.3(98.5 - q_1)}{(q_2-57.3)+(98.5-q_1)} \\ \dfrac{102.8-x}{102.8-q_2}, & if\ x > \dfrac{98.5(q_2-57.3)+57.3(98.5-q_1)<x<98.5}{(q_2-57.3)+(98.5-q_1)} \\ 0, & if\ x \ge 102.8 \end{cases}$$

For Diastolic Blood Pressure UMF and LMF High

$$\overline{\mu}_{DiastolicBP}(High)(x) = \begin{cases} 0, & x \le 90.6 \\ \dfrac{x-90.6}{q_1 - 90.6}, & if\ 90.6 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{117-x}{117-q_2}, & if\ q_2 \le x \le 117 \\ 0, & if\ x > 117 \end{cases}$$

$$\underline{\mu}_{DiastolicBP}(High)(x) = \begin{cases} 0, & x \le 92.3 \\ \dfrac{x-92.3}{q_2 - 92.3}, & if 92.3 \le x \le \dfrac{115(q_2 - 92.3)+92.3(115 - q_1)}{(q_2-92.3)+(115-q_1)} \\ \dfrac{117-x}{117-q_2}, & if\ x > \dfrac{115(q_2-92.3)+92.3(115-q_1)<x<115}{(q_2-92.3)+(115-q_1)} \\ 0, & if\ x \ge 117 \end{cases}$$

For Diastolic Blood Pressure UMF and LMF Very High

$$\overline{\mu}_{DiastolicBP}(VeryHigh)(x) = \begin{cases} 0, & x \le 111.3 \\ \dfrac{x-111.3}{q_1 - 111.3}, & if\ 111.3 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{134.9-x}{134.9-q_2}, & if\ q_2 \le x \le 134.9 \\ 0, & if\ x > 134 \end{cases}$$

$$\underline{\mu}_{DiastolicBP}(VeryHigh)(x) = \begin{cases} 0, & x \le 112.4 \\ \dfrac{x-112.4}{q_2 - 112.4}, & if 112.4 \le x \le \dfrac{134(q_2 - 112.4)+112.4(134 - q_1)}{(q_2-112.4)+(134-q_1)} \\ \dfrac{134.9-x}{134.9-q_2}, & if\ x > \dfrac{134(q_2-112.4)+112.4(134-q_1)<x<134}{(q_2-112.4)+(134-q_1)} \\ 0, & if\ x \ge 134.9 \end{cases}$$

For Diastolic Blood Pressure UMF and LMF Severe

$$\overline{\mu}_{DiastolicBP}Severe(x) = \begin{cases} 0, & x \le 128.2 \\ \dfrac{x-128.2}{q_1 - 128.2}, & if\ 128.2 \le x \le q_1 \\ 1, & if\ q_1 \le x \le q_2 \\ \dfrac{148.5-x}{148.5-q_2}, & if\ q_2 \le x \le 148.5 \\ 0, & if\ x > 148.5 \end{cases}$$

$$\underline{\mu}_{DiastolicBP}(Severe)(x) = \begin{cases} 0, & x \le 131 \\ \dfrac{x-131}{q_2 - 131}, & if 131 \le x \le \dfrac{146(q_2 - 131)+131(146 - q_1)}{(q_2-131)+(146-q_1)} \\ \dfrac{148.5-x}{148.5-q_2}, & if\ x > \dfrac{146(q_2-131)+131(146-q_1)<x<146}{(q_2-131)+(146-q_1)} \\ 0, & if\ x \ge 148.5 \end{cases}$$

**Table 3. Membership function values for Shock Prediction.**

| Linguistic Term | Upper Membership Function | Lower Membership Function |
|---|---|---|
| Low | 0,0.1733,0.3 | 0.0282,0.173,0.271 |
| Normal | 0.2,0.3532,0.5 | 0.234,0.3558,0.464 |
| High | 0.4,0.5833,0.8 | 0.43,0.584,0.7666 |
| Very High | 0.6,0.806,1 | 0.632,0.806,0.9718 |

In this paper, 900 fuzzy rules are defined based on (4) and part of the rules are presented in *Fig. 5* while sample rule is given as;

If HeartRate is low and Respiratory Rate is normal and Temp is very high and Blood Pressure is high THEN Prediction is high.

| 1 | | | | | |
|---|---|---|---|---|---|
| 2 | Heart Rate | Respiratory Rate | Temp | BP | Patient Risk Level |
| 3 | Low | low | low | low | high |
| 4 | Low | low | low | normal | low |
| 5 | Low | low | low | high | high |
| 6 | Low | low | low | veryhigh | high |
| 7 | Low | low | normal | severe | veryhigh |
| 8 | Low | low | normal | low | high |
| 9 | Low | low | normal | normal | low |
| 10 | Low | low | normal | high | low |
| 11 | Low | low | high | veryhigh | high |
| 12 | Low | low | high | severe | veryhigh |
| 13 | Low | low | high | low | low |
| 14 | Low | low | high | normal | minimal risk |
| 15 | Low | normal | veryhigh | high | high |
| 16 | Low | normal | veryhigh | veryhigh | high |
| 17 | Low | normal | veryhigh | severe | veryhigh HD |
| 18 | Low | normal | veryhigh | low | low |
| 19 | Low | normal | low | normal | low |
| 20 | Low | normal | low | high | low |
| 21 | Low | normal | low | veryhigh | minimal risk |
| 22 | Low | normal | low | severe | very highrisk |
| 23 | Low | normal | normal | low | risk |

**Fig. 5. Rule base for cardiac patient shock level prediction.**

Given the crisp input vector $v = [55, 25, 7, 135]$, their degree of memberships is calculated from the respective triangular membership functions as shown in *Table 3*. *Table 4* presents the firing rules based on the set input values. Rule evaluation of the firing rules 20, 21, 165, 51, 100, 101, 35 and 36 against the fuzzy set in *Table 3* yields the result in *Table 5*. The Karnik Mendel Type reduction model is applied by selecting the leftmost (*L*) and rightmost (*R*) switch points. In our study, the switch point is selected at $L=5$ and $R = 2$ and then we compute for the values of $y_l$ and $y_r$ using *Eqs. (24)* and *(25)*, respectively. The defuzzification is carried out using *Eq. (26)*.

**Table 3. Fuzzified value (fuzzy set).**

| **Lingusitic Variable** | | | | |
|---|---|---|---|---|
| HeartRate $[\overline{\mu}^1, \underline{\mu}^1]$ (55) | Respiratory Rate$[\overline{\mu}^2, \underline{\mu}^2]$ (25) | Body Temp. $[\overline{\mu}^3, \underline{\mu}^3]$ (7) | Systolic Blood Pressure $[\overline{\mu}^4, \underline{\mu}^4]$ (135) | Diastolic Blood Pressure $[\overline{\mu}^4, \underline{\mu}^4]$ (102) |
| $U_L$[1.644,0.053] | $U_N$[2.067,0.197] | $U_L$[0.649,0.569] | $U_H$[0.360,1.579] | $U_H$[0.950,0.9065] |
| $U_N$[0.154,0.062] | $U_H$[0.129,0.170] | | $U_{VH}$[0.659,0.455] | |

**Table 4. The firing rules.**

| **Rule No.** | **Firing Interval** | **Consequent** |
|---|---|---|
| R20 | $\overline{f}^1, \underline{f}^1, ]$ = [1.644*2.067*0.649*0.360, 0.053*0.197*0.569*1.579] = [0.360, 0.053] | $[\overline{y}^1, \underline{y}^1]$ = L[0.149, 1.525] |
| R21 | $\overline{f}^2, \underline{f}^2, ]$ = [1.644*2.067*0.649*0.659, 0.053*0.197*0.589*0.455] = [0.649,0.053] | $[\overline{y}^2, \underline{y}^2]$ =M[0.3497, 0.6598] |
| R165 | $[\overline{f}^3, \underline{f}^3, ]$= [0.129*2.067*0.649*0.360, 0.170*0.197*0.569*1.579] = [0.129,0.170] | $[\overline{y}^3, \underline{y}^3]$= L[0.105, 0.631] |
| R51 | $[\overline{f}^4, \underline{f}^4, ]$=[0.1544*2.067*0.649*0.659, 0.062*0.197*0.569*0.455]=[0.154,0.062] | $[\overline{y}^4, \underline{y}^4]$=L[0.15, 0.1525] |
| R100 | $[\overline{f}^5, \underline{f}^5]$=[1.644*0.129*0.649*0.360, 0.053*0.170*0.569*1.579]=[0.129,0.053] | $[\overline{y}^5, \underline{y}^5]$=H[0.60, 0.598] |
| R101 | $[\overline{f}^6, \underline{f}^6]$ =[1.644*0.129*0.649*0.659' 0.053*0.170*0.569*0.455]=[0.129,0.053] | $[\overline{y}^6, \underline{y}^6]$= VH[0.80, 0.798] |
| R35 | $[\overline{f}^7, \underline{f}^7, ]$=[2.067*0.129*0.649*0.360, 0.197*0.170*0.569*1.579]=[0.129,0.170] | $[\overline{y}^7, \underline{y}^7]$=L[0.148,0.1525] |
| R36 | $[\overline{f}^8, \underline{f}^8, ]$=[2.067*0.129*0.649*0.659, 0.197*0.170*0.569*0.455]=[0.129,0.170] | $[\overline{y}^8, \underline{y}^8]$=H[0.5302, 0.5975] |

The defuzzification is carried out using

$$y_l = \min_{L\in[1,N-1]} \frac{\sum_{n=1}^{L} \overline{f}^n \underline{y}^n + \sum_{n=L+1}^{N} \underline{f}^n \underline{y}^n}{\sum_{n=1}^{L} \overline{f}^n + \sum_{n=L+1}^{N} \underline{f}^n}. \tag{26}$$

$$y_r = \max_{R\in[1,N-1]} \frac{\sum_{n=1}^{R} \underline{f}^n \overline{y}^n + \sum_{n=R+1}^{N} \overline{f}^n \overline{y}^n}{\sum_{n=1}^{R} \underline{f}^n + \sum_{n=R+1}^{N} \overline{f}^n}. \tag{27}$$

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The switch point for *L=5* and *R = 2*,

$$y_l = \frac{\bar{f}^1\underline{y}^1 + \bar{f}^2\underline{y}^2 + \bar{f}^3\underline{y}^3 + \bar{f}^4\underline{y}^4 + \bar{f}^5\underline{y}^5 + \underline{f}^6\underline{y}^6 + \underline{f}^7\underline{y}^7 + \underline{f}^8\underline{y}^8}{\bar{f}^1 + \bar{f}^2 + \bar{f}^3 + \bar{f}^4 + \bar{f}^5 + \underline{f}^6 + \underline{f}^7 + \underline{f}^8}. \tag{28}$$

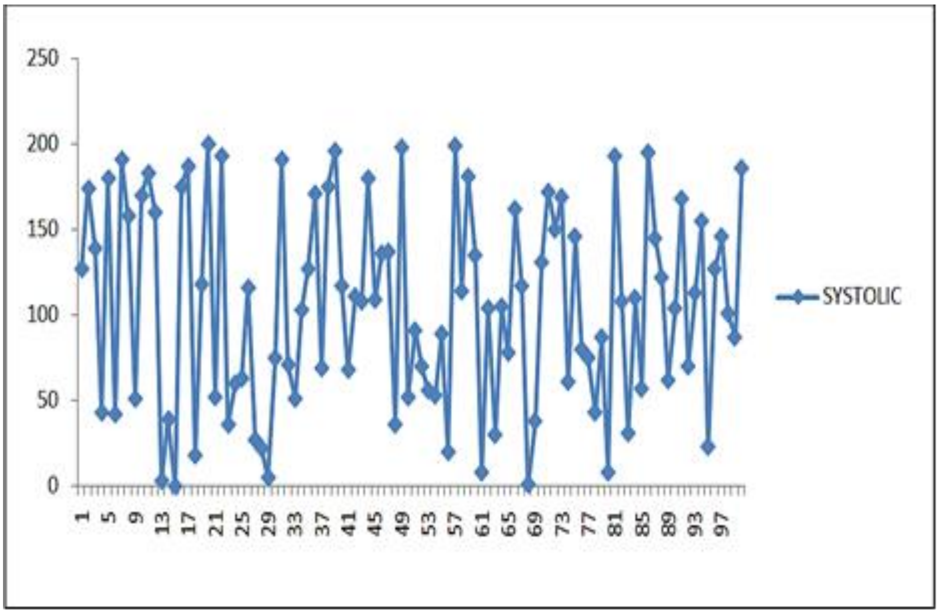
$$y_r = \frac{\underline{f}^1\bar{y}^1 + \underline{f}^2\bar{y}^2 + \bar{f}^3\bar{y}^3 + \bar{f}^4\bar{y}^4 + \bar{f}^5\bar{y}^5 + \bar{f}^6\bar{y}^6 + \bar{f}^7\bar{y}^7 + \bar{f}^8\bar{y}^8}{\underline{f}^1 + \underline{f}^2 + \bar{f}^3 + \bar{f}^4 + \bar{f}^5 + \bar{f}^6 + \bar{f}^7 + \bar{f}^8}. \tag{29}$$

$$y_l = \frac{\begin{array}{c} 0.360 * 1.525 + 0.649 * 0.6598 + 0.129 * 0.631 + 0.154 * 0.1525 \\ + 0.129 * 0.598 + 0.053 * 0.798 + 0.170 * 0.1525 + 0.170 * 0.5975 \end{array}}{0.360 + 0.649 + 0.129 + 0.154 + 0.129 + 0.053 + 0.170 + 0.170} = 1.9997.$$

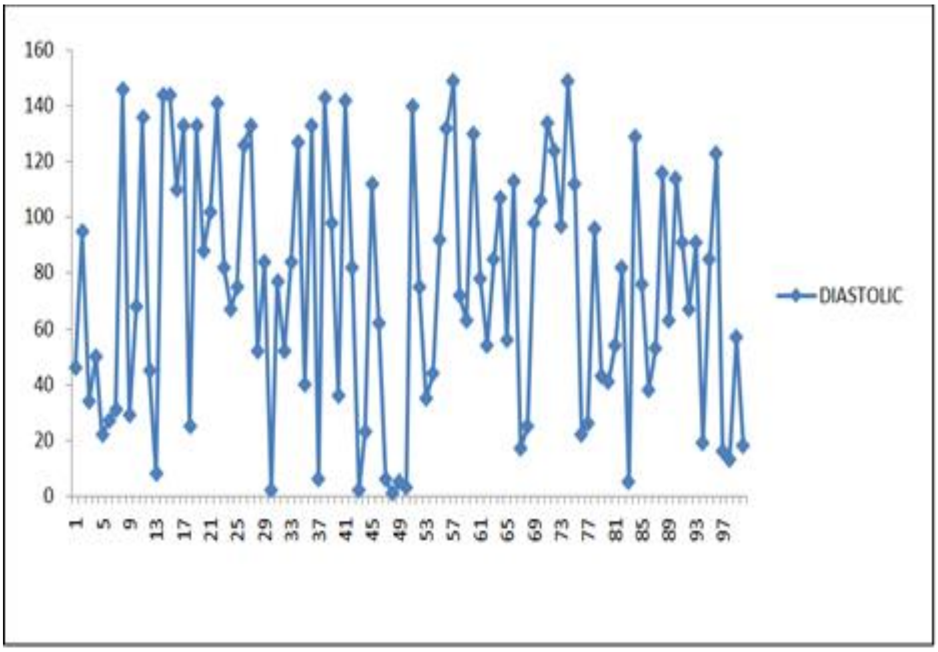
$$y_r = \frac{\begin{array}{c} 0.053 * 0.149 + 0.053 * 0.3497 + 0.129 * 0.105 + 0.154 * 0.15 \\ + 0.129 * 0.60 + 0.129 * 0.80 + 0.129 * 0.148 + 0.129 * 0.5302 \end{array}}{0.053 + 0.053 + 0.129 + 0.154 + 0.129 + 0.129 + 0.129 + 0.129} = 0.36593.$$

## 5| Results and Discussion

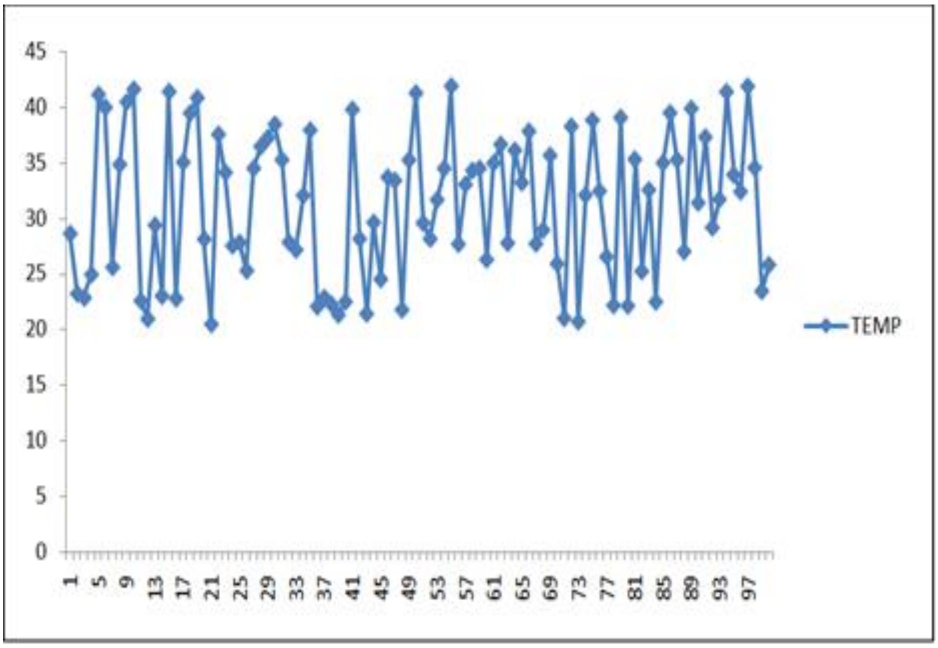
In this paper, experimental results for prediction problem as applied to predicting shock level in cardiac patients using interval type-2 fuzzy logic system have been presented. The effectiveness and generalization capability of IT2FLS have been tested using 1000 datasets obtained from University of Uyo Teaching Hospital and Federal Medical Centre, Yenagoa all in Nigeria. *Table 1* shows part of the details of the cardiac patient's health datasets. Five cardiac health variables namely: systolic blood pressure, diastolic blood pressure, temperature, heart rate and respiratory rate served as the input while cardiac shock level served as the desired output. Triangular membership function was employed for fuzzification of the input. Fuzzy inference was derived using Mamdani inference process. Investigation of the performance of IT2FLS and that of its type-1 counterpart were carried out. Statistical evaluation was carried out using performance metrics of Mean Absolute Difference (MAD), Mean Absolute Percentage Error (MAPE), Mean Square Error (MSE) and Root Mean Squared Error (RMSE), respectively. *Fig. 6* shows the plots of transformed cardiac patients' health dataset for (a) blood pressure diastolic, (b) blood pressure systolic, (c) temperature, (d) respiratory rate, and (e) heart rate, respectively.




(a)




**(b)**




**(c)**

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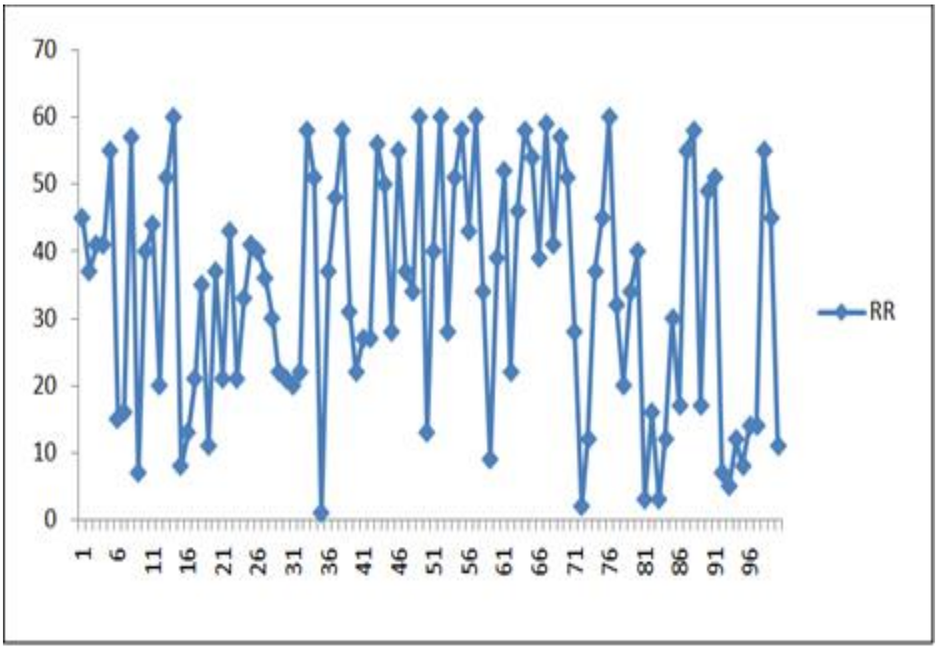
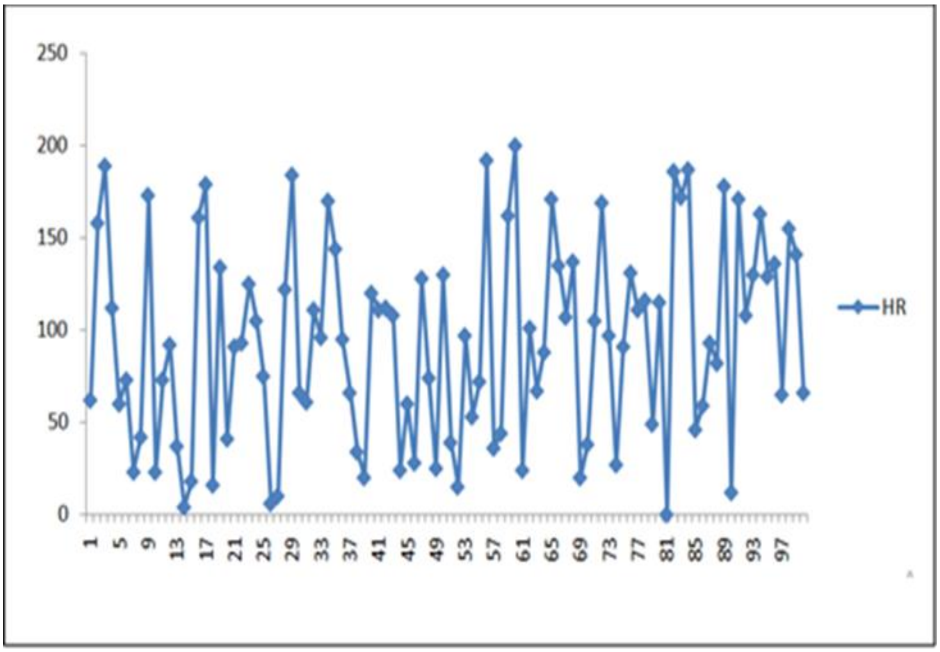



(d)

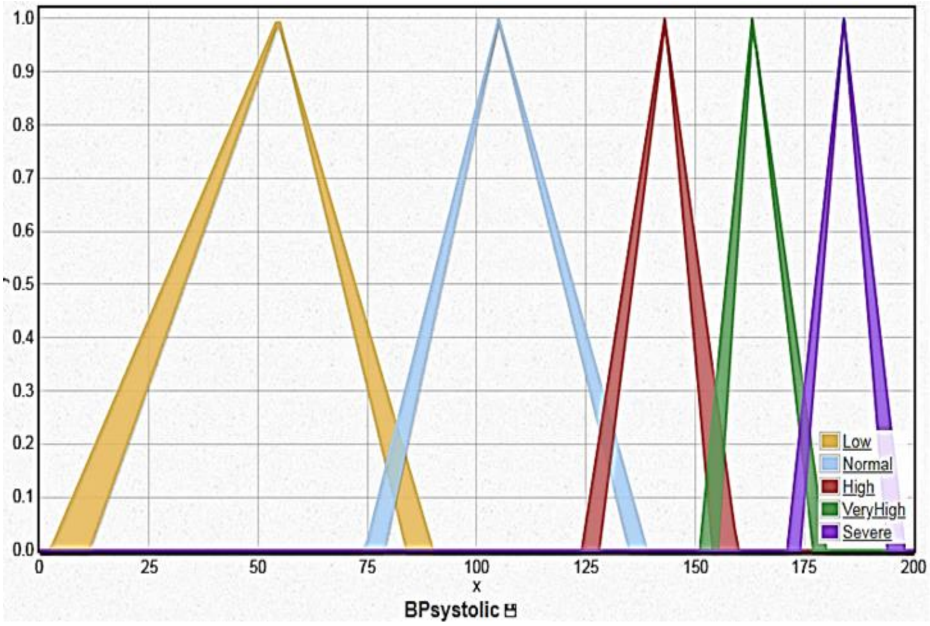



(e)

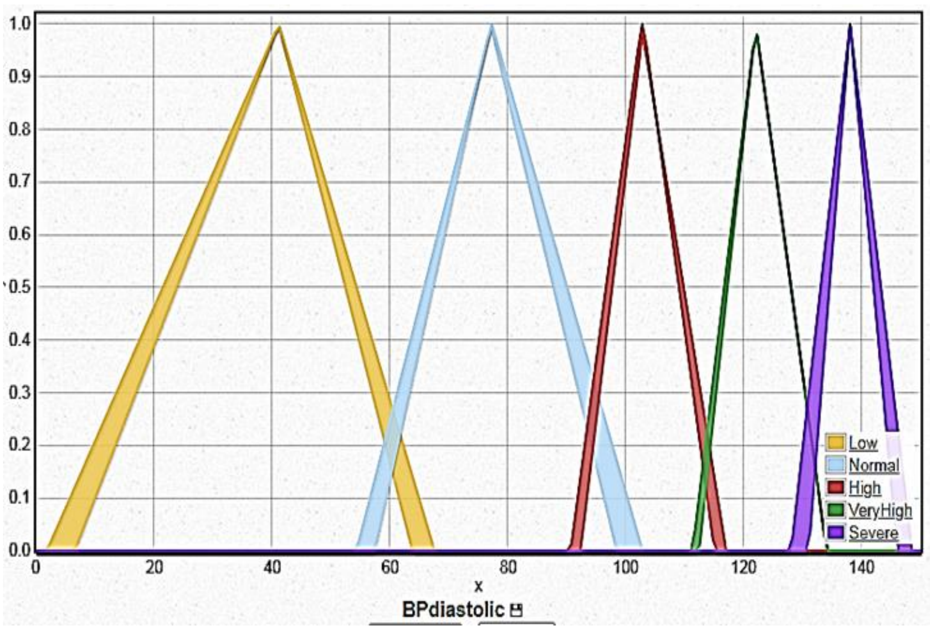
**Fig. 6. Plots of the transformed cardiac patients' health dataset for (a) blood pressure diastolic, (b) blood pressure systolic, (c) temperature, (d) respiratory rate, (e) heart rate.**

## 5.1| Interval Type-2 Fuzzy Logic Results for Remote Vital Signs Monitoring and Shocks Level Prediction

With the fuzzy rule-base of Fig. 4 and both the input and output membership functions plots are depicted in *Fig. 7(a-e)*, respectively. Applying the IT2FLC to the proposed problem, we obtain the system's response. *Fig. 8* gives the prediction results for IT2FLS. *Fig. 9* presents the system's response of the IT2FLS for the actual and predicted shock level.




(a)




(b)

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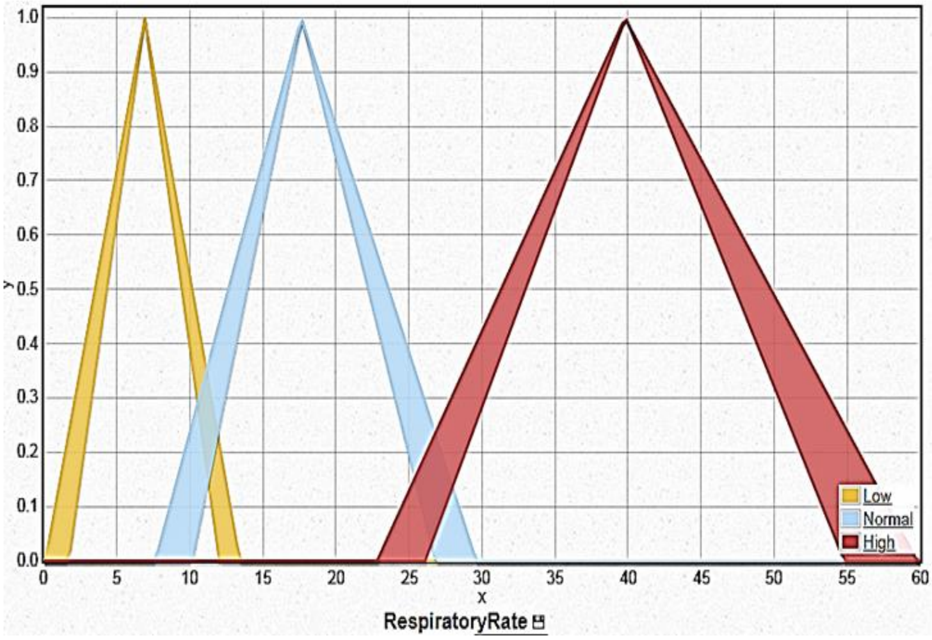
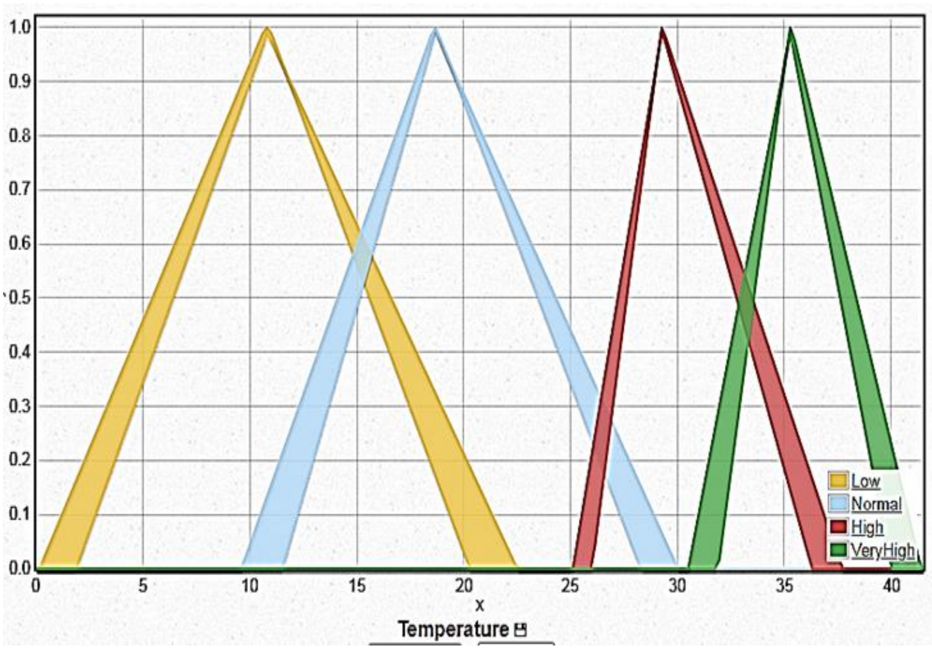

1.0
0.9
0.8
0.7
0.6
y
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
45
50
55
60
x
RespiratoryRate
Low
Normal
High

(c)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
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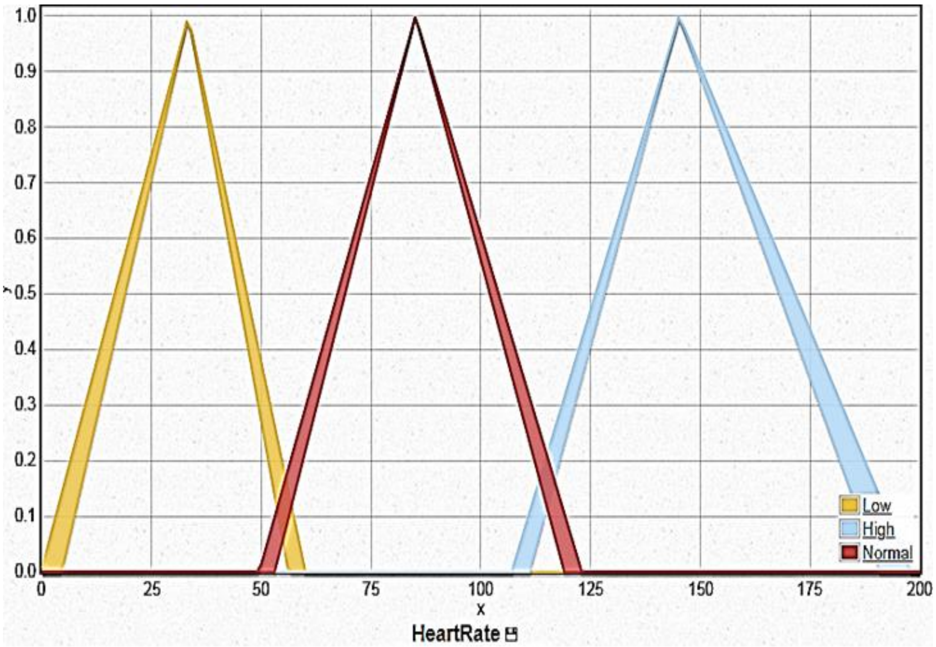
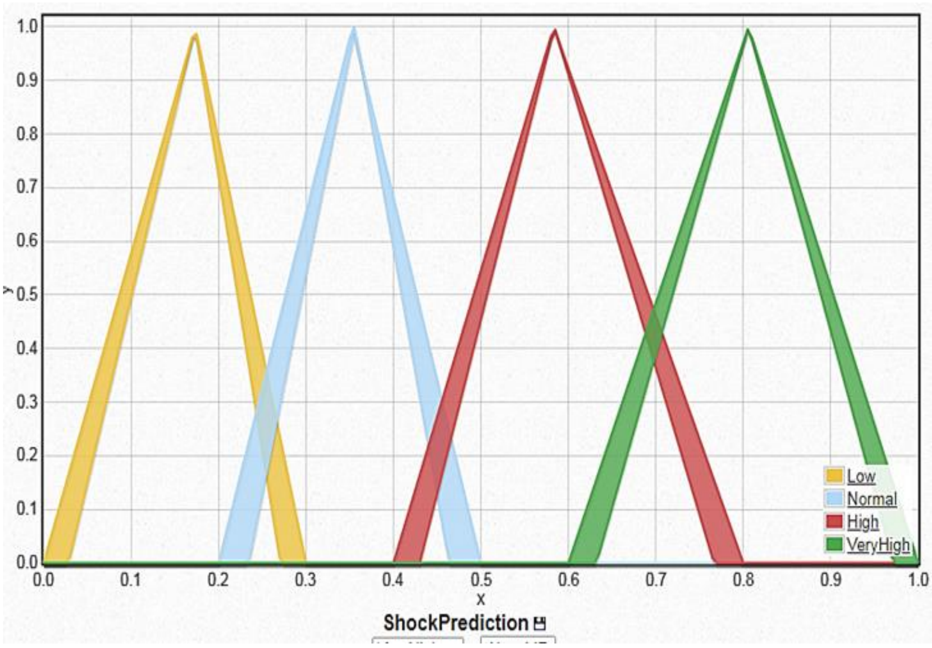
5
10
15
20
25
30
35
40
x
Temperature
Low
Normal
High
VeryHigh

(d)




(e)




(d)

**Fig. 7. Inputs and output membership functions plot for (a) bp-diastolic (b) bp-systolic (c) temperature (d) respiratory rate (e) heart rate and (f) shock level prediction.**

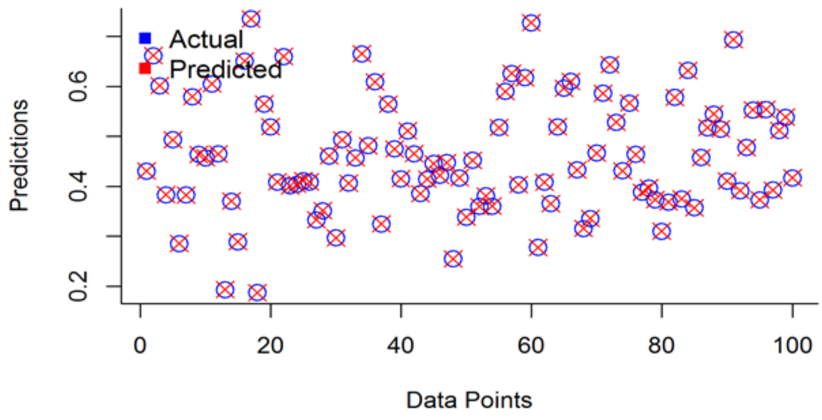



Fig. 8. The prediction results for (a) IT2FLS.

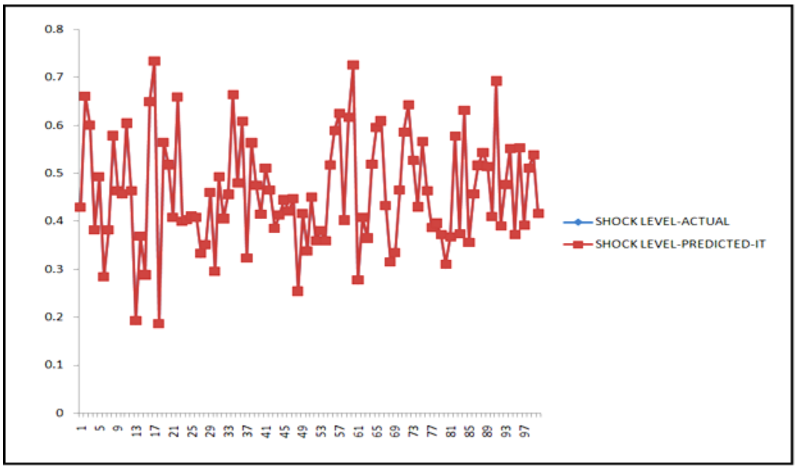



Fig. 9. System's response of the IT2FLS for the actual and predicted shock level.

## 5.2| Type-1 Fuzzy Logic Results for Remote Vital Signs Monitoring and Shocks Level Prediction

*Fig. 10* gives the prediction results for T1FLS while *Fig. 11* presents the system's response of the T1FLS for the actual and predicted shock level. *Fig. 12* shows the plots of the system's response for the actual shock level and predicted shock level for T2FLS and T1FLS.

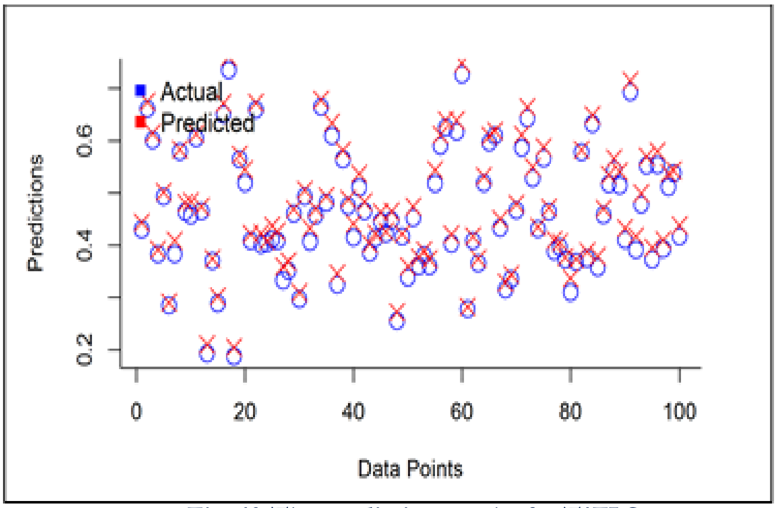



*Fig. 10.* The prediction results for T1FLS.

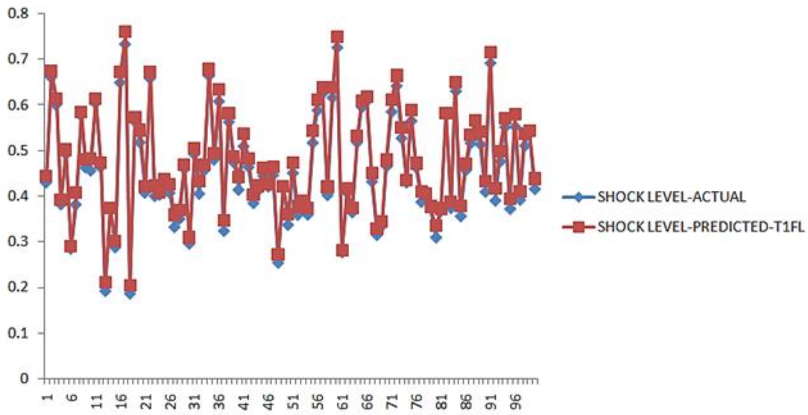



Fig. 11. System's response of T1FLS for the actual and predicted shock level.

## 5.3| Performance Evaluation

*Fig. 12* and *Table 5* give the results of the performance of IT2FLS with that of T1FLS where, shock level-actual is the actual shock level, Shock Level-Predicted-IT2FLS is the predicted shock level by IT2FLS and Shock Level-Predicted-T1FLS is the predicted shock level by T1FLS, respectively. Statistical analysis for comparison is also made between IFLS and IT2FLS. Two experiments are conducted in order to explore these analyses. In each case, the performance metrics are the MSE and the RMSE. *Figs. 13-15* show the plots of the two models using their test MSEs and RMSEs. *Figs. 13 (a)* and *(b)* give the prediction errors for IT2FLS and T1FLS, while the prediction accuracy of IT2FLS and T1FLS are shown in *Figs.14* (a) and (b). *Figs. 15* (a) and (b) gives the error models against error values for IT2FLS and T1FLS, respectively. *Table 6* compares the performance of IT2FLS with that of T1FLS with respect to MSE and RMSE. The results of the statistical comparison of the model performance are presented in *Table 6*.

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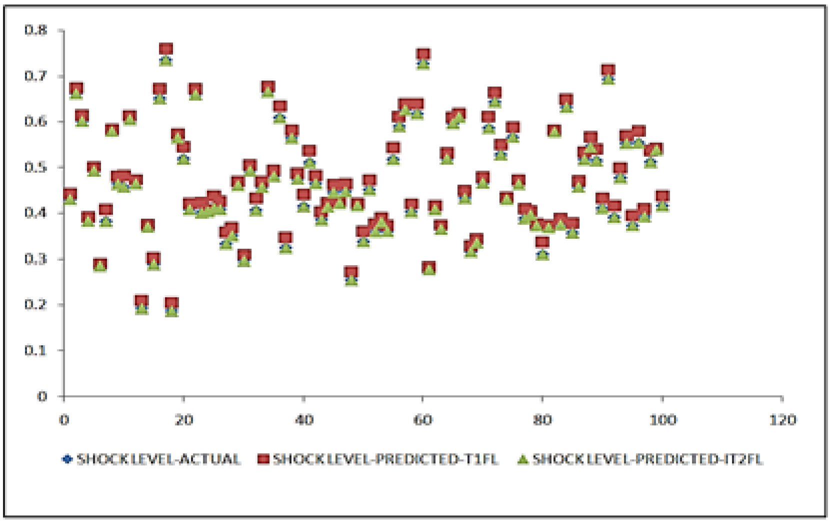


**Fig. 12. Plots of the system's response of actual shock level and predicted shock level for IT2FLS and T1FLS.**

From *Fig. 12* it is observed that with the use of IT2FLS, the model is able to model uncertainty adequately in predicting shock level of a cardiac patient and in many applications better than the T1FLS. Also, with MFs that are intervals, the IT2FLS is able to model uncertainty in predicting shock level of a cardiac patient in many applications better than T1FLS which MFs are not represented as intervals values.

## 6| Conclusion

This paper investigated the predictive capability of Interval Type-2 Fuzzy Logic System (IT2FLS) based on Mamdani fuzzy inference and applied to in monitoring and predicting shock level in cardiac patients. Implementation of conventional Type-1 Fuzzy Logic System (T1FLS) was carried out for the purpose of comparison. By the use of IT2FLS, we have been able to predict different shock levels for cardiac patients. Specifically, the following conclusions are made:

- *The IT2FLS copes with more information and handle more uncertainties in health data.*
- *The IT2FLS performs significantly well compared to TIFLS with model errors of 0.0005 against 0.079.*
- *The IT2FLSs with interval MF can reduce the effects of uncertainties in most health applications.*

In the future, we intend to explore Tagaki Sugeno Kang (TSK) fuzzy inference to conduct more experiments using the same data sets. Also, we intend to optimize our system using flower pollination algorithm for performance improvement. More so, we will apply other fuzzy modeling functions such as triangular and trapezoidal functions, respectively.

**Table 5. Results of shock level actual and predicted for T2FLS and T1FLS.**

| S/No. | Shock Level-Actual | Shock Level-Predicted IT2FLS | Shock Level-Predicted T1FLS |
|---|---|---|---|
| 1. | 0.430209738 | 0.430534538 | 0.443508938 |
| 2. | 0.661076429 | 0.661401229 | 0.674375629 |
| 3. | 0.600932789 | 0.601582389 | 0.614556789 |
| 4. | 0.382681769 | 0.383006569 | 0.391656169 |
| 5. | 0.492674633 | 0.492999433 | 0.501649033 |
| 6. | 0.284818273 | 0.285467873 | 0.289792673 |
| 7. | 0.381977912 | 0.382627512 | 0.408576312 |
| 8. | 0.578692885 | 0.579342485 | 0.583667285 |
| 9. | 0.463544732 | 0.463869532 | 0.481168732 |
| 10. | 0.456734044 | 0.457383644 | 0.483332444 |
| 11. | 0.604593743 | 0.605243343 | 0.613892943 |
| 12. | 0.464519101 | 0.464843901 | 0.473493501 |
| 13. | 0.192299351 | 0.192948951 | 0.210248151 |
| 14. | 0.369657904 | 0.370307504 | 0.374632304 |
| 15. | 0.28822936 | 0.28887896 | 0.30185336 |
| 16. | 0.650264118 | 0.650588918 | 0.672212918 |
| 17. | 0.734445205 | 0.734770005 | 0.760718805 |
| 18. | 0.186542266 | 0.187191866 | 0.204491066 |
| 19. | 0.564212161 | 0.564861761 | 0.573511361 |
| 20. | 0.518631549 | 0.518956349 | 0.544905149 |
| 21. | 0.408237197 | 0.408561997 | 0.421536397 |
| 22. | 0.659320718 | 0.659645518 | 0.672619918 |
| 23. | 0.400810079 | 0.401134879 | 0.422758879 |
| 24. | 0.403371577 | 0.404021177 | 0.408345977 |
| 25. | 0.410957191 | 0.411606791 | 0.437555591 |
| 26. | 0.408079746 | 0.408729346 | 0.426028546 |
| 27. | 0.332620921 | 0.333270521 | 0.359219321 |
| 28. | 0.350599807 | 0.351249407 | 0.368548607 |
| 29. | 0.46014474 | 0.46079434 | 0.46944394 |
| 30. | 0.296303978 | 0.296628778 | 0.309603178 |
| 31. | 0.492720862 | 0.493045662 | 0.506020062 |
| 32. | 0.40598575 | 0.40631055 | 0.43225935 |

## 6.1| Ethical Issues

Ethical issues came to play in this research as the research involved gathering data from cardiovascular patients' records. However, the research was not involved in the direct collection of the data, but a review of patients' files and medical histories after due permission was granted by the responsible authorities. Hence, we discuss the ethical issues under two areas:

– *Consent form. The consent form through written permission was obtained from the health authority before embarking on the research. A sample of the authorization clearance is used by the ethical committee of Federal Medical Centre, Yenagoa and University Teaching Hospital, Uyo*
– *Data protection. Data protection is ensured by not revealing patients' personal details such as Name, Address, Occupation and many others. Hence, data gathered excluded this information.*

**Table 6. Comparison of T1FLS and IT2FLS in shock level prediction.**

| Models | Performance | MSE | RMSE |
|---|---|---|---|
| T1FLS | Prediction Error | 0.004 | 0.018 |
| | Model Error | 0.0003 | 0.079 |
| | Prediction Accuracy | 0.9997 | 0.9821 |
| IT2FLS | Prediction Error | 0.0001 | 0.0006 |
| | Model Error | 2.57E-07 | 0.0005 |
| | Prediction Accuracy | 1 | 0.9995 |

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